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by

K W Whyte

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Meteorological Office
London Road
Bracknell
Berkshire
RG12 2SZ
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UNITED KINGDOM

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ABSTRACT

Two techniques for the height assignment of semi-transparent cirrus using Meteosat IR and WV imagery and the radiative transfer model RTTOV are investigated. Their essential equivalence is demonstrated and results from a case study are presented. Adaptation of the method for use in Nimrod is described and the outcome of a parallel trial of the system in Nimrod and the mesoscale model is reported. Reasons for the poor results are discussed.

1. Introduction

An important factor in the operation of the Nimrod short-term forecasting system is the correct analysis of cloud observations via the Moisture Observation Pre-processing System (MOPS) (Macpherson et al, 1996a,c), leading to correct assimilation of cloud into the Mesoscale Model. It is particularly important that errors arising from failure to recognise semi-transparent or sub-pixel cloud in satellite imagery are avoided, since cloud inserted incorrectly at medium levels can lead to the triggering of mid-level instability, and hence spurious model rainfall, especially in the early stages of the forecast (Macpherson et al, 1996a,b).

This report describes the results of experimenting with two essentially equivalent techniques (referred to here as the "Eumetsat" and the "Minimum residual" methods) for generating cloud-top temperatures from Meteosat imagery, taking account of the possible presence of semi-transparent or sub-pixel cloud. It also deals with the adaptation of these techniques for use within Nimrod, and the consequential effects (as observed in a parallel trial) on the Mesoscale Model. Both cloud-top temperature methods make use of measurements in the 11μm infrared (IR) and 6μm water vapour (WV) channels, together with a radiative transfer model. The radiative transfer model used for both methods in this work was the RTTOV model (Eyre, 1991) currently used by the Satellite Soundings group, extended with appropriate coefficients calculated for the Meteosat-5 and Meteosat-6 IR and WV channels. Forecast temperature and humidity profiles for use as input to RTTOV were obtained from the Mesoscale Model.

Detailed descriptions of the two techniques are given and their essential equivalence is shown in section 2. Results from a particular case study are described in section 3, and adaptation of the method for use in Nimrod is described in section 4. Results from the parallel trial are given in section 5, and conclusions and recommendations for future work are given in section 6.

2. Descriptions of the techniques

The two methods investigated were the "Eumetsat" or water vapour intercept method,

developed for the height assignment of cloud-motion winds, and described in Appendix C of Schmetz et al (1993) and in Menzel et al (1993), and the "minimum residual" method of Eyre and Menzel (1989).

2a. "Eumetsat" method

The "Eumetsat" technique was developed for operational use on the 32×32–pixel areas used for cloud-motion winds, and was originally described by Bowen and Saunders (1984). It is essentially an automated graphical method requiring the calculation of the intersection point of two curves in IR–WV radiance space: one the line determined by representative values for a clear and cloudy pixel within each 32×32–pixel region, the other the curve formed by using a radiative transfer model to calculate the theoretical IR and WV radiances from the forecast temperature and humidity profile with an opaque cloud layer inserted successively at different levels. A single layer of broken or semi-transparent cloud is assumed. For this work the method was initially adapted for implementation on Mesoscale Model grid squares, ie areas of about six pixels rather than 32×32.

The detailed implementation of this technique is as follows.
For each mesoscale grid box:

(i) From the mesoscale model forecast temperatures and humidities for the appropriate time for that grid point, interpolate to the levels required by the RTTOV radiative forward model, and calculate the theoretical radiances which would be observed by the Meteosat IR and WV channels, for opaque cloud at various levels and for a clear atmosphere.

(ii) Calculate the regression line of WV on IR for the (usually) six pairs of IR/WV radiance values which map to that grid square, and the pair of theoretical clear radiances obtained from (i). Other ways of constructing the line are possible, but this method avoids giving too much weight to the inferred clear radiances compared to the measured radiances.

(iii) In IR–WV radiance space, construct the curve defined by the points calculated in (i), and determine its intersection with the line calculated in (ii). The corresponding IR brightness temperature can then be used to interpolate between model levels, and the corresponding interpolated model temperature value defines the cloud-top temperature of any semi-transparent or broken sub-pixel cloud. Examples of such constructions are shown in figure 1a–d. Following Bowen and Saunders (1984), any IR radiances within 15 counts or WV radiances within 10 counts of the clear radiance were ignored, and if the regression line failed to intersect the curve, then the model temperature corresponding to maximum IR radiance was used.

2b. "Minimum residual" method

The second technique is the "minimum residual" method described by Eyre and Menzel (1989). In this technique the sum of the squares of the differences between the measured and calculated radiances for the IR and WV channels is minimised, for a variable cloud

amount and height. Calculated radiances again depend on the forecast profile and a suitable radiative transfer model, so for this work the modified RTTOV has again been used.

The technique was implemented as follows.
For each mesoscale grid box:

(i) From the Mesoscale Model's forecast temperature and humidity profiles, and using the RTTOV radiative forward model, calculate for both the IR and WV channels the clear radiances (R_i^c, R_w^c) and the overcast radiances $(R_i^o(p), R_w^o(p))$ for cloud at different pressure levels.

(ii) The radiance in each channel is assumed to be a linear combination of the clear and opaque radiances, ie

$$R_i = (1 - N)R_i^c + N R_i^o(p)$$

and

$$R_w = (1 - N)R_w^c + N R_w^o(p)$$

for some pressure level p, where for sub-pixel opaque cloud N is the fractional cloud amount. For semi-transparent cloud N is the product of the cloud fraction and the emissivity, assumed to be the same in each channel. (The other assumption being made, as for the "Eumetsat" method, is that just one cloud layer is present.)

The sum of the squares of the residuals in the two channels is then

$$\delta_i^2 + \delta_w^2 = \sum_{j=i,w} [(R_j^m - R_j^c) - N(R_j^o(p) - R_j^c)]^2$$

where the R_j^m are the measured radiances.

If this is minimised with respect to N, then

$$N = \frac{\sum_{j=i,w}(R_j^m - R_j^c)(R_j^o(p) - R_j^c)}{\sum_{j=i,w}(R_j^o(p) - R_j^c)^2}$$

and

$$\delta_i^2 + \delta_w^2 = \sum_{j=i,w} (R_j^m - R_j^c)^2 - N^2(R_j^o(p) - R_j^c)^2$$

Both N and $\delta_i^2 + \delta_w^2$ are calculated for various p.

(iii) p and N are chosen to minimise $\delta_i^2 + \delta_w^2$. Given the initial linear assumption, this is exactly equivalent to finding the intersection of the line in IR–WV radiance space joining the clear radiance pair to the measured radiance pair with the curve defined by the opaque radiances, ie the "Eumetsat" method. N is given by the fractional distance along the line from the "clear" point to the intersection, of the point defined by the measured radiance pair.

The cloud-top temperature for each Meteosat pixel can then be found from the temperature profile at pressure level p, and the average of these gives a cloud-top temperature for the grid square. The same criteria as for the "Eumetsat" method are used for abandoning the calculation if the IR or WV radiance is too close to the clear radiance.

Although the two methods are essentially equivalent, the difference between them as implemented for this work is that the "minimum residual" method produces as many different cloud-top temperatures as there are measured radiance pairs, whereas the "Eumetsat" method pools all the measured values to produce one estimate by generating the regression line through all the values together with the "clear" point. In general the differences between results obtained by the two methods are relatively minor, but occasional large differences can occur as a result of differences in quality control. For example, in a case where the two lines fail to intersect, the Eumetsat method is programmed to use the maximum measured IR value to obtain a surface/cloud-top temperature. In the same case, the "minimum residual" method may well obtain a result corresponding to the top of the troposphere. The real answer in such circumstances is likely to be that the model atmosphere is incorrect in some way.

3. Results and conclusions from initial trials

The two methods outlined above are illustrated using data for 27 March 1996. The raw data were the 1200UTC B-format Meteosat IR and WV channel imagery, and temperature and humidity profiles derived from the 12-hour forecast fields from the midnight run of the Mesoscale Model were used as input to the RTTOV radiative transfer model.

Figures 2a and 2b show the calibrated reprojected IR and WV channel imagery for 1200UTC on 27 March 1996. The northern third of the area is covered by an extensive cloud sheet, while there are clearly other smaller areas of high cloud in the south. The main feature of the WV image is a well-marked east-west band of dry air across the southern half of the area.

The results from both techniques (figures 3a and 3b) maintain the regions of higher cloud while extending their areas somewhat. With the exception of a spurious area of high cloud in the region of the dry band (see figure 1d discussion below) the results of the two techniques are again very similar, except in detail. One feature evident in both figures 3a and 3b is a thin line of cold cloud tops which follows the continental coastline. This effect is thought to be caused by incorrect surface temperatures (sea instead of sea/land) in the radiative transfer model, leading to incorrect results from both techniques.

Figure 1a shows a typical result from the area of opaque cloud in the north, with the measured values almost on the model curve, while figure 1b shows a similar result from nearer the edge of the same cloud sheet, where the position of the plotted measured values indicates around 0.4–0.5 effective cloud cover.

Figure 1c is for a grid square where the use of both techniques has been automatically rejected, because the measured values are too close to the model clear point according

to the criteria specified in section 2.

Figure 1d is for a square within the area of spurious high cloud generated by the "minimum residual" method. For the "Eumetsat" technique, it is a case of non-intersecting curves, and so the maximum IR value has been used. The solution reached by the "minimum residual" method is to choose the highest atmospheric level available, since this gives the lowest residual errors. It may well be a case of the simulated WV counts from RTTOV being too high at lower levels, and that the measured points correspond to low cloud and would fit well on a more realistic curve.

Figure 4 shows the effective fractional cloud amount from the "minimum residual" method, and figure 5 the differences (for the "Eumetsat" method) between the derived cloud-top temperature and the IR brightness temperature. This illustrates how (as might be expected) the largest differences are on the edges of the cloud sheets.

The two implementations described above of what is essentially the same method have been shown to be capable of yielding realistic estimates of cloud-top temperature in the 27 March 1997 example and other cases which have been studied. It was concluded that provided adequate quality control safeguards were implemented, the use of this technique in Nimrod should lead to an improved handling of semi-transparent cirrus in particular, but also of sub-pixel cloud whose tops are not too low to influence the radiance in the water vapour channel. In order to avoid the possiblity of significant errors in the derived cloud-top temperatures, output should probably be restricted to grid squares where the derived effective cloud fraction is at least two oktas.

Although the two implementations are essentially equivalent, the differences in detail can lead to erroneous results in particular cases. Using both techniques allows each to be used as a check on the other, and for results to be discarded when they differ significantly. Figures 6 shows, for the particular case which has been described, the areas which yield satisfactory results given the restrictions of cloud-top temperature < -30C and effective cloud fraction > 0.3. A further restriction which requires similar results from both techniques removes the area of spurious high cloud, and gives the result shown in figure 7.

4. Adaptation for use in Nimrod

For use within the Nimrod code, the method has been further adapted. Both techniques are carried out using imagery interpolated onto the 5km Nimrod grid (NG projection), with Mesoscale model input taken from the files available on Nimrod, normally forecast fields from the previous 6-hourly model run, interpolated to a 15km grid on the same NG projection. The existing Nimrod cloud-top height program has been modified so that it runs the RTTOV radiative transfer model for each point on the 15km grid, providing that at least one of the nine corresponding points on the 5km grid is cloudy according to the cloudcover determined by the Nimrod combined IR and VIS cloud detection algorithm. Then the "Eumetsat" and "minimum-residual" methods are executed separately for each cloudy 5km pixel, and provided the derived cloud heights agree within one RTTOV level, the level is higher than 500hPa and the cloud amount is greater than 0.25, the "minimum-residual" result is used. Otherwise the program calculates the cloud height in the same way as before (Macpherson et al, 1996c, henceforth

referred to as the "old" method).

A number of experiments with this alternative Nimrod cloud-top height program were carried out in preparation for a full parallel trial. The results from these tests showed that the method as adapted for Nimrod produced very plausible results in terms of the changed cloud height and amount.

However there are a number of sources of potential errors which must be taken into consideration in the application of the method operationally. A particular problem is when there is more than one layer of cloud. In this situation, if information were available independently about the height and fractional cover of a lower cloud layer, then the appropriate radiances from that cloud layer could be used in place of the theoretical clear radiances. Failing this, the correction to the cloud-top temperature from the method which has been described is still in the right direction, but the temperature will be overestimated by an amount depending on the characteristics of both cloud levels. The greater the amount of low-level cloud and the smaller the amount of high-level cloud, the larger the error.

Clearly, any inaccuracies in the radiances calculated by the modified RTTOV radiative transfer model will lead to errors in the derived cloud-top temperatures. A sensitivity test was carried out on the case described in section 3, in order to assess the effect of a 2K increase in simulated WV brightness temperatures from RTTOV with a view to obtaining realistic error estimates for the calculated cloud-top temperatures. Results showed that 45% of grid squares with derived cloud-top temperature < -30C and effective cloud fraction > 0.3 were more than 5 degrees K colder than before. Again, larger errors are generated for pixels with low cloud amounts. Figure 8 shows the histogram of cloud-top temperature differences.

Another source of potential error is the assumption that emissivities in the IR and WV channels are equal. Baran (personal communication) has shown that variation in ice-crystal type can cause a difference in emissivities between the 11μm and 6μm channels equivalent to 4K in brightness temperature.

5. Results from parallel trials

Results from initial trials with the Nimrod code were considered to be sufficiently encouraging to proceed to a full parallel trial involving the mesoscale model. A first parallel trial in December 1996 gave generally inconclusive or marginally detrimental results, but it was discovered that there had been an error in the code as implemented on Nimrod, resulting in the omission of humidity information at a number of levels. Consequently the trial was repeated in March 1997. There was now a clear detrimental effect on the model forecasts of precipitation. A typical case is that of 12UTC on 11 March 1997, for which the Meteosat IR and WV imagery is shown in figure 9, and when much of the western side of the British Isles was covered by thin cirrus.

Figure 10 shows clear and cloudy areas as determined by the standard Nimrod cloud-cover scheme using Meteosat IR and VIS imagery, and the areas where the cloud top height has been adjusted by the new scheme. However for much of the area over Ireland and to the north and south of Ireland the new scheme failed to generate a valid result,

and so in these areas Nimrod has reverted to using the current operational scheme, ie the "old" method. On examination of the output of the new cloud-top height scheme, it is clear that in these areas the new scheme usually failed because the measured WV radiance was too close to the simulated WV radiance generated by RTTOV for a clear atmosphere or for low cloud (ie within the limit of ten counts, about 4K in brightness temperature), and so the presence of cirrus could not be reliably inferred.

Figure 11 is for a pixel near the Scilly Isles, and is typical of how the new scheme has behaved in these areas. The result has been discounted because the measured WV count is just seven less than the RTTOV-generated clear WV count, and from the form of the graph it is clearly not possible to deduce with any degree of confidence the height of the cloud, which could have a cloud-top temperature anywhere between -20 and -40C. However since other evidence (surface observations and the striated appearance of the imagery, even more apparent in AVHRR) indicates that the cloud is cirrus, it would be expected to be colder still, which indicates that the level of simulated WV counts from RTTOV for a clear atmosphere or one with a layer of low cloud is too low.

The effect on the model of this failure by the new cloud-top height scheme to generate realistic cloud heights over a sufficiently large area is shown in figure 12. Spurious rainfall has been generated by the trial version of the model to the north and south of Ireland. Because quality control for cloud insertion in the model had been relaxed, medium-level cloud from the "old" cloud-top height scheme was allowed into the model resulting in the spurious rain. Where the effective amounts of thin cirrus were sufficient for the new scheme to operate, over much of Wales and the Irish Sea, no rain was generated by the model.

6. Conclusions and recommendations

It is clear that for the Mesoscale Model to use quantitatively a cloud-top height analysis from Nimrod incorporating the new scheme would be unacceptable. As the March 1997 experiment has shown, even if the new scheme improves the diagnosis of semi-transparent cirrus, it still allows the possibility of areas of undiagnosed cirrus being assigned to medium levels by the "old" cloud-top height scheme, so causing spurious convective rainfall in the model. Consequently the present model quality control, whereby no cloud is assimilated in areas where the model already contains cirrus, must be continued. However the new scheme could be used to extend this quality control so that no cloud is inserted for any model grid square which contains at least one pixel where the new scheme has analysed cirrus, on the principle that adjacent pixels are also likely to contain cirrus, albeit possibly small amounts which cannot be reliably diagnosed.

Given the sensitivity of the method to the level of simulated WV radiances, it is also important that the detailed operation of RTTOV within the Nimrod code is assessed, to decide whether the level of simulated WV radiances is correct or whether there is a systematic bias.

Once a satisfactory formulation of the basic scheme has been introduced, an investigation could also be carried out into an extension of the method to situations with two cloud layers. If information were available independently about the height and

fractional cover of a lower cloud layer, then the appropriate radiances from that cloud layer could be used in place of the theoretical clear radiances.

7. Acknowlegments

Thanks are due especially to Peter Rayer, who generated the coefficients describing the characteristics of the Meteosat IR and WV channels, to Richard Renshaw, who modified the RTTOV code so that it could use them, and to Byron Chalcraft, Adam Maycock, Richard Graham and Will Hand, who were responsible for setting up the parallel trial. Useful conversations have been held with Bruce Macpherson and Brian Golding, and with John Eyre and other members of the Satellite Applications section. Pauline Jackson assisted with the programming.

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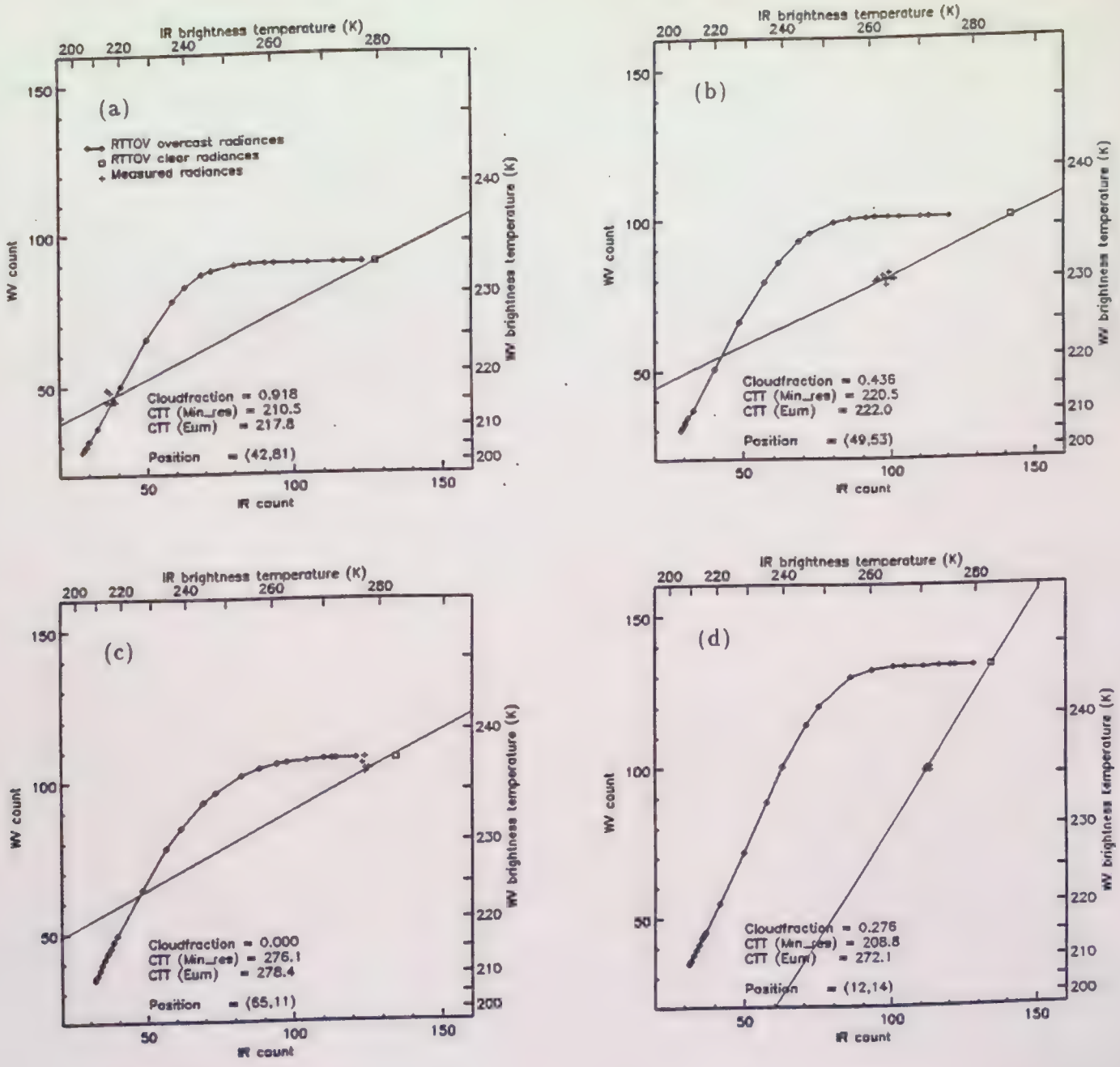

Figure 1. 27 March 1996. Simulated and measured radiances for the positions indicated in figure 2.

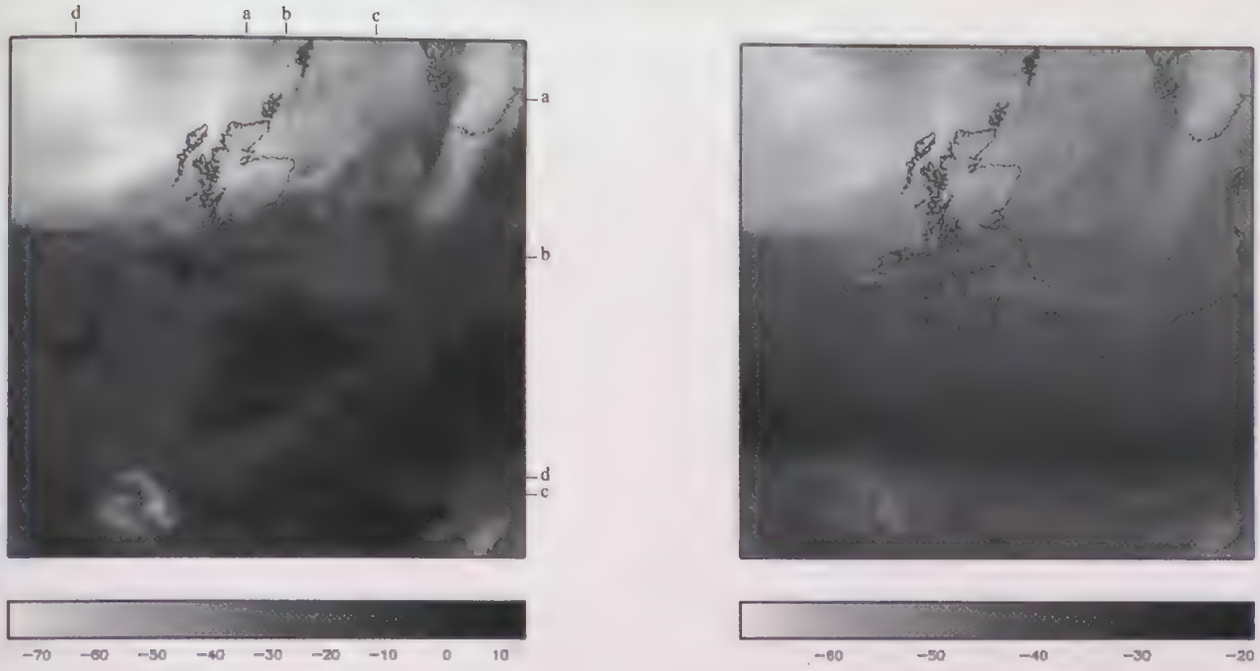

Figure 2. Meteosat brightness temperatures

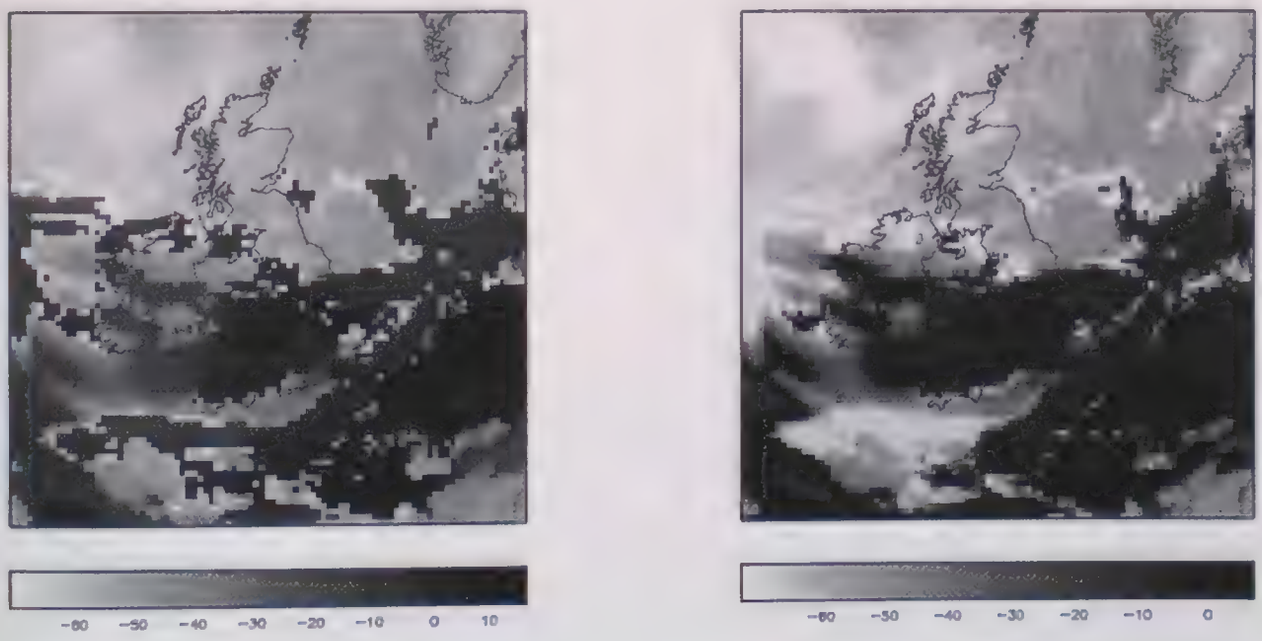

Figure 3. Cloud-top temperatures calculated by the two techniques

27 March 1996 1200UTC

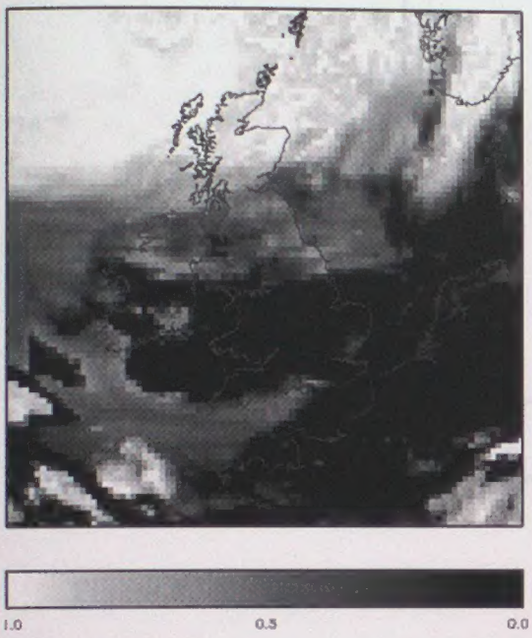

Figure 4. Effective fractional cloud amount

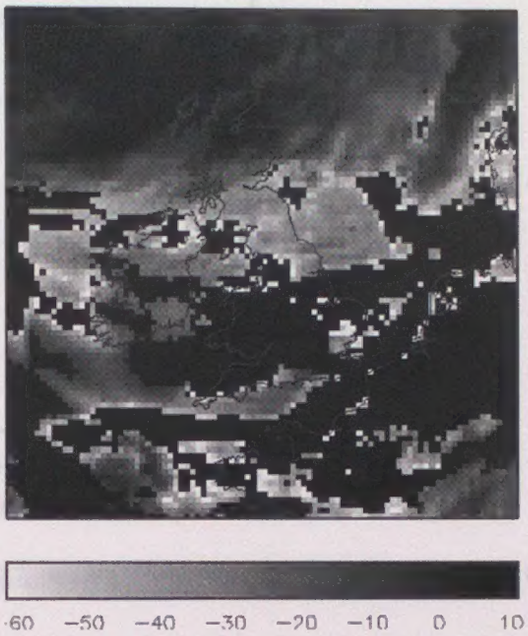

Figure 5. "Eumetsat" CTT - IR brightness temperature

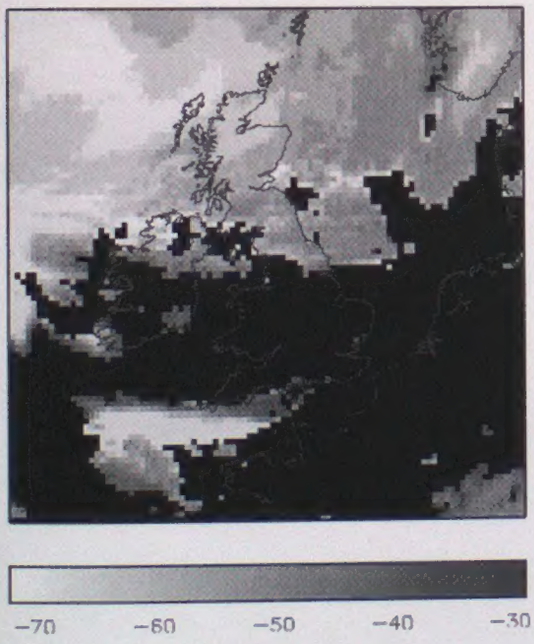

Figure 6. "Minimum residual" CTT <-30C with N>=0.3

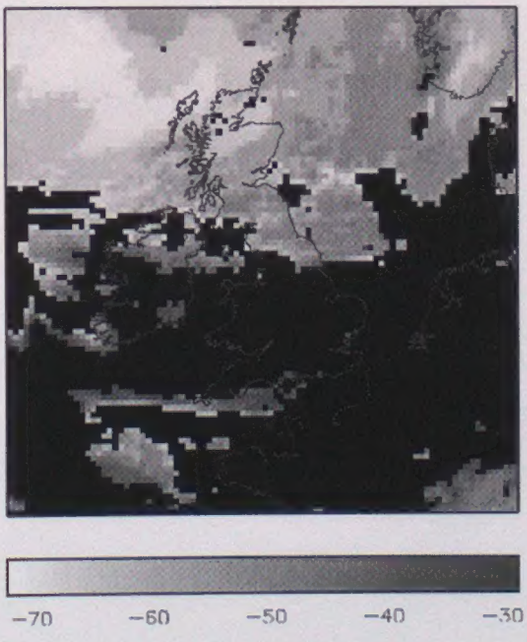

Figure 7. As figure 6, with difference between techniques <10C

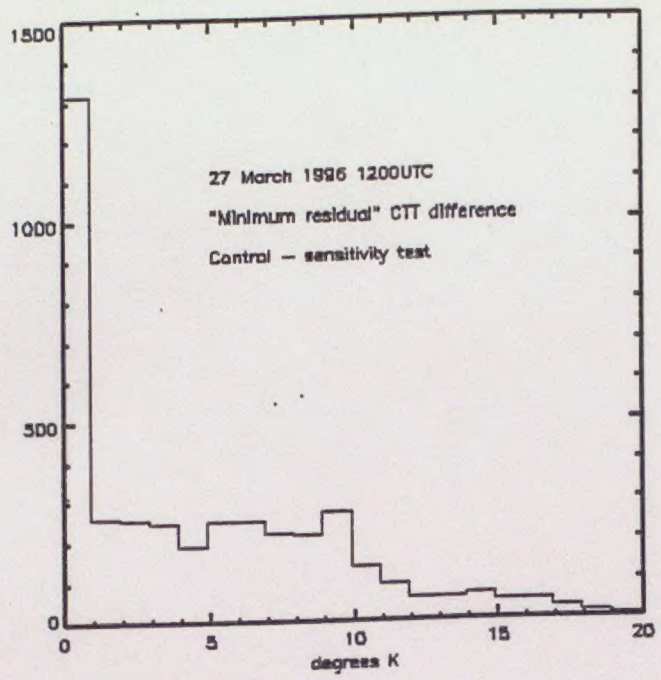

Figure 8. Histogram of cloud-top temperature differences from the RTTOV sensitivity test.

11 March 1997 1200UTC

(a) IR

(b) WV

Figure 9. Meteosat brightness temperatures

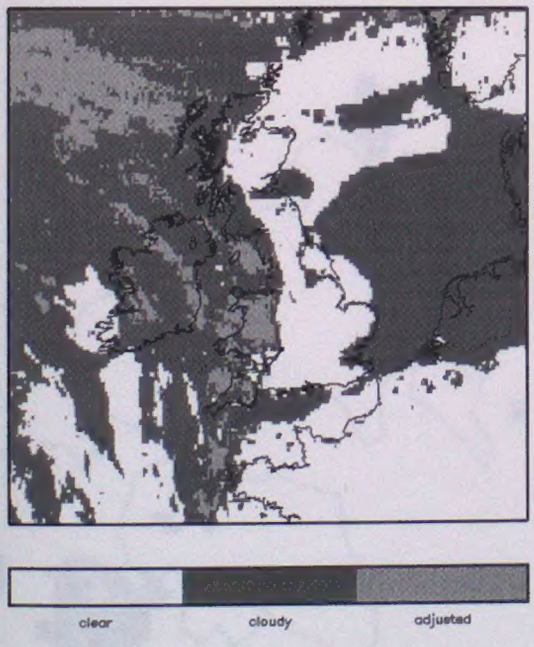

Figure 10. Cloudcover, showing regions of height adjustment

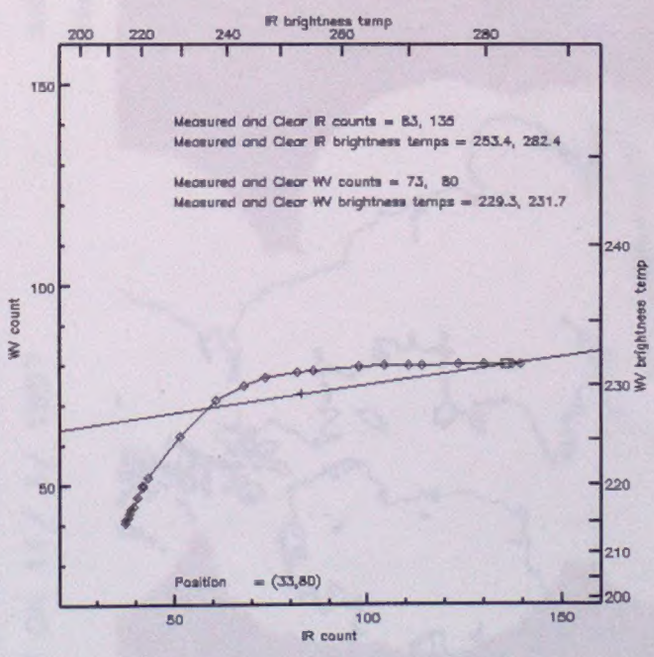

Figure 11. Simulated and measured radiances at position indicated in figure 9

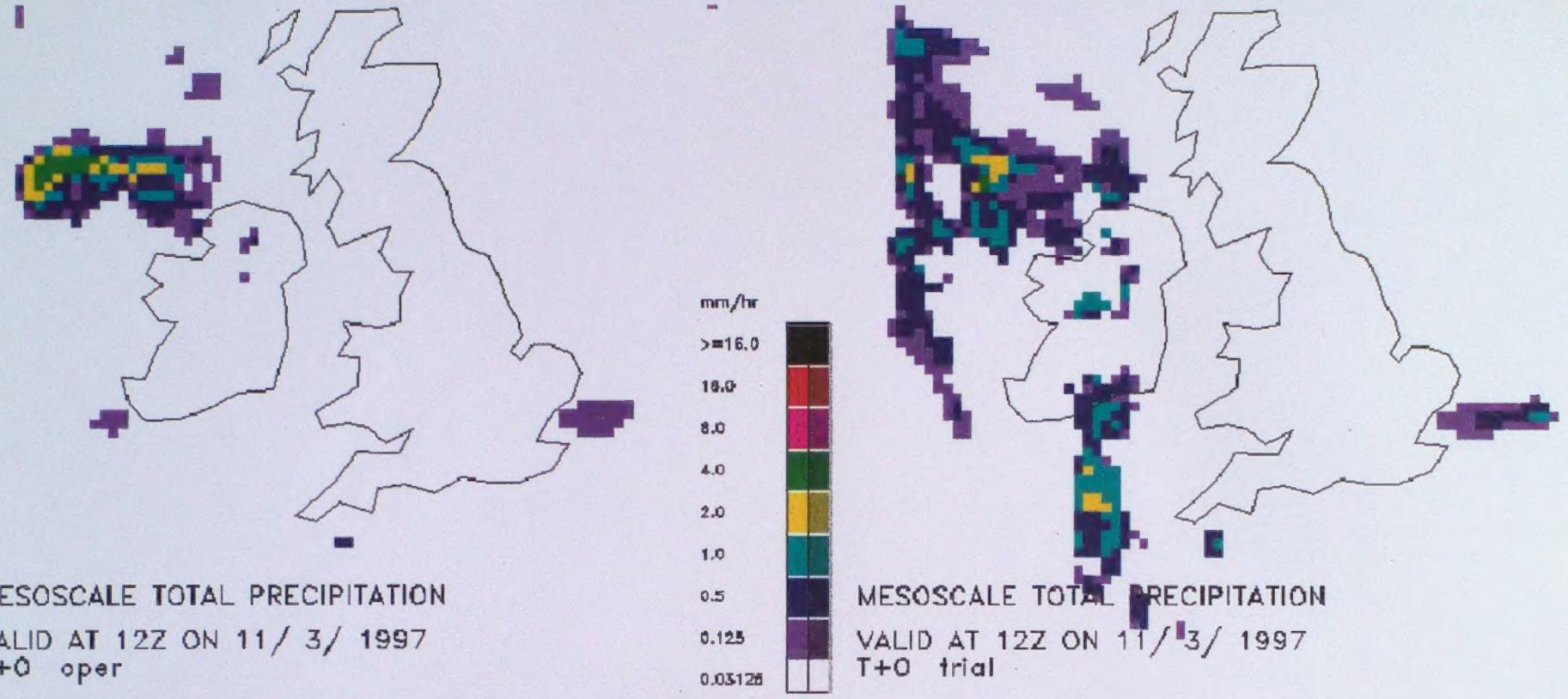

Figure 12. Model and radar rainfall